LBNL-47352

The Impact of Blowing Agents on Residential Water Heater Performance

Alex Lekov
Jim Lutz
Camilla Dunham Whitehead
James McMahon

Energy Efficiency Standards Group
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

March 2001

As published in the *Proceedings of the 52nd Annual International Appliance Technical Conference*,
Columbus, OH, March 26-28, 2001

This work was supported by the Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ABSTRACT

The National Appliance Energy Conservation Act of 1987 (NAECA) requires the U.S. Department of Energy (DOE) to consider amendments to the energy conservation standards to increase energy efficiency in residential water heaters. A driving force affecting efficiency is the ozone-depletion regulation regarding blowing agents for insulation in all water heater fuel types. This paper presents results of cost and efficiency impacts of three potential blowing agents.

Residential water heaters are typically insulated with polyurethane foam in the space between the tank and the jacket. Currently, water heater manufacturers use HCFC-141b, an ozone-depleting substance, as a blowing agent. After 2003, as a result of the Montreal Protocol (1993), manufacturers must use blowing agents that do not deplete the ozone layer. The analysis presented in this paper considers three replacement candidates, HFC-245fa, HFC-134a, and cyclopentane by comparing their efficiency and cost effectiveness when applied to water heater insulation.

This analysis used computer simulation models and other analytical methods to investigate the efficiency improvements due to different design options, when alternative blowing agents are applied. The calculations were based on the DOE test procedure for residential water heaters. The analysis used average manufacturer, retailer, and installer costs to calculate the total consumer costs. Consumer operating expenses were calculated based on modeled energy consumption under test procedure conditions and U.S. average energy prices. With this information, a cost-efficiency relationship was developed to show the average manufacturer and consumer cost to achieve increased efficiency.

INTRODUCTION

Overall energy efficiency of a residential water heater is measured in terms of an energy factor (EF) and is determined by the DOE test procedure.[1] To reduce heat loss, water heaters are insulated. The insulation is foamed in place using polyols and isocyanurates which react to form polyurethane foam. The heat of reaction vaporizes a blowing agent included in the mixture, creating a frothy mass that quickly hardens into closed-cell foam insulation. The choice of insulation is critical to achieving high water heater efficiency at a reasonable cost. Since essentially all water heaters use foam insulation, the savings potential affects all fuel types. Currently all manufacturers are using the hydrofluorocarbon HCFC-141b as the blowing agent. However, HCFC-141b is an ozone-depleting substance and will be phased out in January, 2003.[2] Therefore, the water heater industry, like all other industries that use this chemical, must find an appropriate replacement. It is important to note, that although the topic of this study is related to the current update of the water heater efficiency standards, the study itself addresses water heater efficiency changes made in response to new environmental concerns.

Options for non-ozone depleting blowing agents include HFC-245fa, HFC-134a, cyclopentane, and HFC 365mfc, as well as combinations of these blowing agents. The U.S. Environmental Protection Agency's (EPA) Clean Air Act guides the U.S. appliance industry on replacement of HCFC/CFC blowing agents. The EPA's Significant New Alternatives Program (SNAP) approves chemicals and technologies to replace ozone depleting chemicals. Of the options listed above, all except HFC-365mfc have been approved by the EPA/SNAP.[3]

Table 1 lists three characteristics of these blowing agents. All of the replacements have Zero Ozone Depletion Potential.[4] Cyclopentane is widely used in Europe and is inexpensive. It is highly flammable and U.S. water heater manufacturers have been hesitant about accepting it. HFC-134a is currently available, but its thermal conductivity is higher than other alternatives and it is expected to be more expensive. HFC-365mfc may be a good alternative, but it also has a higher thermal conductivity and its price is unknown. In 1999, one manufacturer announced it had received EPA approval to produce HFC-245fa.

Table 1. Blowing Agents Characteristics

	Ozone Depletion Potential	**Global Warming Potential**	**Cost *** ***$/lb***
HCFC-141b	0.11	0.1400	1.00
HFC-245fa	0.00	0.2400	1.32
HFC-356mfc	0.00	0.2100	na
HFC-134a	0.00	0.2400	1.50
Cyclopentane	0.00	0.0030	0.80

*This cost covers the blowing agent and all other components of the insulation.

For this analysis, five steps were followed: 1) identify the baseline model and blowing agent characteristics to which design options would be added, 2) identify design options that are expected to increase energy efficiency, 3) estimate manufacturing costs, 4) estimate consumer costs to purchase, install, and operate higher efficiency water heaters, and 5) delineate efficiency potentials and payback periods. Residential electric and gas-fired water heaters of a typical size, i.e., 50-gal (190-l) electric and 40-gal (150-l) gas-fired were considered. The analysis' results show the relationship between the total consumer costs and increased efficiency. Results of this analysis were used to select and rank order the combination of design options.[5]

BASELINE UNITS AND BLOWING AGENT CHARACTERISTICS

Baseline units provide the starting point for analyzing design options for energy efficiency improvements. For each fuel type, the baseline unit was one that just met the existing standard. Table 2 shows characteristics of the baseline water heaters.

Three alternative blowing agents, two hydrofluorocarbons (HFC-245fa and HFC-134a) and cyclopentane, were considered in this analysis. Published data of the properties of the insulation blown with of the three agents were used.[6]

HFC-245fa is being already adopted as a blowing agent by the refrigerator industry and should be available in sufficient quantity by 2003 for use in water heaters as well.[7] Reports from Bayer Corporation and Battelle show that HFC-245fa does have a slightly higher conductivity than the current blowing agent for the temperatures found in water heaters.[8] The average increase in conductivity resulting from replacing HCFC-141b with HFC-245fa is 3.0%.

Table 2. General Characteristics of Water Heaters Baseline Units

Characteristics	Electric	Gas
Rated Volume	50-gallon (190-l)	40-gallon (150-l)
Insulation Blowing Agent	HCFC-141b	HCFC-141b
Insulation Thickness (nom.)	1.5 in. (3.8 cm)	1 in. (2.5 cm)
Rated Input	4,500 W	40,000 Btu/hr (11,700 W)
Ignition System	N/A	Pilot at 450 Btu/hr (120W)
Energy Factor (EF)	0.86	0.54
Recovery Efficiency (RE)	98%	76%

HFC-134a is already approved by EPA as an acceptable substitute for HFC-141b.[3] This blowing agent is considered a practical alternative to HCFC: it is readily available and can be applied today.[6] A report from Oak Ridge National Laboratory show that HFC-134a does have a higher conductivity than the current blowing agent.[9] The average increase in conductivity resulting from replacing HCFC-141b with HFC-134a is 10.0%. For water heater applications, HFC-134a will probably be blended with other HFCs such as HFC 245fa or HFC 365mfc. Pre-blended HFC 134a is considered one of the easiest replacements from the implementation point of view. Compared to other HFCs (i.e., HFC 245fa), HFC-134a has a higher initial cost, but may require lower loading level (% of total foam), approximately 9% compared to 13%-16%.

Pentane-based foams are beginning to be explored by the water heater industry. Pentane is already approved by the EPA as an acceptable substitute for HCFC-141b[3]. This blowing agent is already a principal component of the rigid foam insulation used as a house insulation material and is available in sufficient quantity. Reports from Battelle show that pentane does have a slightly higher conductivity than HCFC-141b, and its conductivity is comparable to the conductivity of HFC-245fa.[6]

A distinction was made between baseline models containing current technologies and future baseline models that were expected to incorporate two mandated features - flammable vapor ignition requirement* and the U.S. Environmental Protection Agency (EPA) required phase-out by January 1, 2003 of the ozone-depleting HCFC-141b blowing agent currently used by the water heater industry for polyurethane insulation. This requirement will affect the efficiency of all water heaters because of the different physical properties of the new insulation. The current technologies were referred to as "existing" baseline models and the future technologies as "2003" baseline models (the year when new efficiency standards are proposed to take effect).

The energy performance for each of the two baseline models of water heaters were modeled with computer simulation programs. The computer simulations were used to determine the energy-efficiency characteristics of the water heater (e.g., EF, Recovery Efficiency (RE), and standby heat loss coefficient, (UA)), based on the DOE test procedure. For electric water heaters, the analysis used WATSIM, an electric water heater simulation program.[10] For gas-fired water heaters, the analysis used the TANK simulation tool.[11]

Computer simulations of existing baseline models for both fuel types used characteristics of water heaters recently available on the market. See Table 2 for specifications of baseline models. The 2003 baseline models used foam insulation blown with HFC-245fa, HFC-134a or cyclopentane. The efficiency and energy-use characteristics of water heaters with HFC-245fa, HFC-134a and cyclopentane insulation are different from those with HCFC-141b insulation. In order to match the characteristics of water heaters with blowing agents other than HCFC-141b, it was necessary to model the baseline water heaters with slightly thicker insulation.

DESIGN OPTION SELECTION

Changes in design features of water heaters can increase energy efficiency. The blowing agents for the foam insulation considered in this analysis produce different levels of efficiency for the same design options. The design options listed in Table 3 are analyzed in this study. [5]

---

*Manufacturers reached an agreement with the Consumer Product Safety Commission (CPSC) to produce gas-fired water heaters resistant to igniting flammable vapors.

Table 3. Water Heater Design Options

Design Option	Electric	Gas
Heat Trap	Yes	Yes
Insulation Thickness	2", 2.5", 3"	2", 2.5", 3"
Insulated Tank Bottom	Yes	N/A
Plastic Tank	Yes	Side Arm Heater only
Improved Flue Baffle	N/A	78% RE & 80% RE
Electronic Ignition, IID	N/A	Side Arm Heater only
Side Arm Heater	N/A	Yes

MANUFACTURER COSTS

Once the design options and the combinations of design options were selected, the costs to manufacturers and consumers were determined, then the design options were rank ordered according to least cost per unit of energy savings. Manufacturer cost estimates were for a 50-gallon electric water heater, and a 40-gallon gas-fired water heater and were expressed on a per-unit basis as an incremental cost over the 2003 baseline design. Table 4 presents manufacturer cost estimates for the baseline water heaters with HCFC-141b, HFC-245fa, HFC-134a, and cyclopentane.

The material costs for the 2003 baseline models include the difference in material costs between HCFC-141b and the alternative blowing agent models. In addition, in order to resist the ignition of flammable vapors, the manufacturing cost of gas-fired water heaters included a $35 charge. There are some differences in costs; although cyclopentane is the least expensive blowing agent, the baseline model utilizing cyclopentane is the most expensive, because its extreme flammability necessitates large capital investments.

Table 4. Baseline Model Manufacturer Costs

Design	Total Mfg Cost *($)*
Electric Water Heater	
Existing Baseline w/ HCFC-141b	121.73
2003 Baseline w/ HFC-245fa	123.87
2003 Baseline w/ HFC-134a	124.94
2003 Baseline w/ cyclopentane	128.16
Gas-fired Water Heater	
Existing Baseline w/ HCFC-141b	133.78
2003 Baseline w/ HFC-245fa	166.49
2003 Baseline w/ HFC-134a	167.07
2003 Baseline w/ cyclopentane	172.01

Table 5 summarizes costs for incorporating design options into baseline water heaters. The cost data were provided by the Gas Appliance Manufacturers Association (GAMA) and industry consultants.[12] [13]

Table 5. Incremental Manufacturer Costs for Design Options

Design		Incremental Manufacturing Costs ($) Electric	Gas-fired
HFC-245fa:	2.0 in	19.54	17.70
	2.5 in	31.87	29.20
	3.0 in	46.64	43.74
HFC-134a:	2.0 in	20.96	18.94
	2.5 in	31.87	30.82
	3.0 in	46.64	45.74
Cyclopentane:	2.0 in	22.94	21.52
	2.5 in	34.20	32.09
	3.0 in	47.85	45.62
Heat Traps		4.01	3.32
Insulated Tank Bottom		3.91	-
Plastic Tank		27.25	-
Improved Flue Baffle		-	6.44
Electronic Ignition (IID)		-	62.26
Side Arm Heater		-	125.42

RETAIL PRICE AND INSTALLATION COSTS

Retail price used here was defined as the cost to the consumer of the water heating equipment only. Retail price of a baseline water heater was a function of the length of the manufacturer's warranty. Baseline models had up to six-year warranties. All price data came from the Water Heater Price Database.[14] Table 6 shows average retail prices and installation costs for electric and gas-fired water heaters.

Table 6. Average Retail Prices and Installation Costs

Fuel Type	Retail Price ($)	Installation Costs ($)
Electric (50-gallon,190-liter)	182	155
Gas-Fired (40-gallon, 150-liter)	163	159

RESULTS

The design options are compared by payback period. Payback period measures the amount of time needed to recover the additional consumer investment in increased efficiency through lower operating costs. National average energy prices (in 1998$), $0.0788/kWh for electricity and

$6.42/MMBtu for natural gas were used for the payback calculations.[15] The total installed cost was developed by adding sales tax and manufacturer, distributor, and installer markups on to factory costs.

The goal of this analysis was to compare the energy savings potential and costs for different design options in water heaters using different blowing agents. Tables 7a and 7b list the design options considered here.

The analysis then looked at the impact of foam conductivity changes from the different blowing agents on energy factor and energy consumption values. Finally, payback periods were calculated to show the combined impact of consumer cost and increased efficiency for all of the design options for each of the blowing agents being considered.

Table 7a. Electric Water Heater Design Options

	Design Option
A	Baseline (245fa)
B	Heat Traps
C	Heat Traps + Tank Bottom Insulation
D	Heat Traps + Tank Bottom Insulation + 2" Insulation
E	Heat Traps + Tank Bottom Insulation + 2.5" Insulation
F	Heat Traps + 2.5" Insulation + Plastic Tank
G	Heat Traps + 3" Insulation + Plastic Tank

Table 7b. Gas-Fired Water Heater Design Options

	Design Option
A	Baseline (245fa)
B	Heat Traps
C	78% RE (Improved Flue Baffle) + Insulation (1") + Heat Trap
D	78% RE (Improved Flue Baffle) + Increased Insulation (2") + Heat Trap
E	78% RE (Improved Flue Baffle) + Increased Insulation (2.5") + Heat Trap
F	80% RE (Improved Flue Baffle) + Increased Insulation (2") + Heat Trap
G	80% RE (Improved Flue Baffle) + Increased Insulation (2.5") + Heat Trap
H	80% RE (Improved Flue Baffle) + Increased Insulation (3") + Heat Trap

Foam Conductivity Impacts

Thermal measurements of polyurethane foams frequently report a range of conductivity values. Table 8 shows conductivity ranges of the three blowing agents normalized to HCFC-141b's conductivity.[6] The foam aging process affects foam conductivity too.

Table 8. Conductivity Ranges (normalized to HCFC-141b)

Blowing Agent	High	Most Likely	Low
HFC-245fa	1.06	1.03	1.00
HFC-134a	1.21	1.10	1.06
Cyclopentane	1.13	1.06	1.0

Figures 1 and 2 show energy consumption and EF by design options for electric water heaters with HFC-134a as the blowing agent. The results are similar for the other blowing agents.

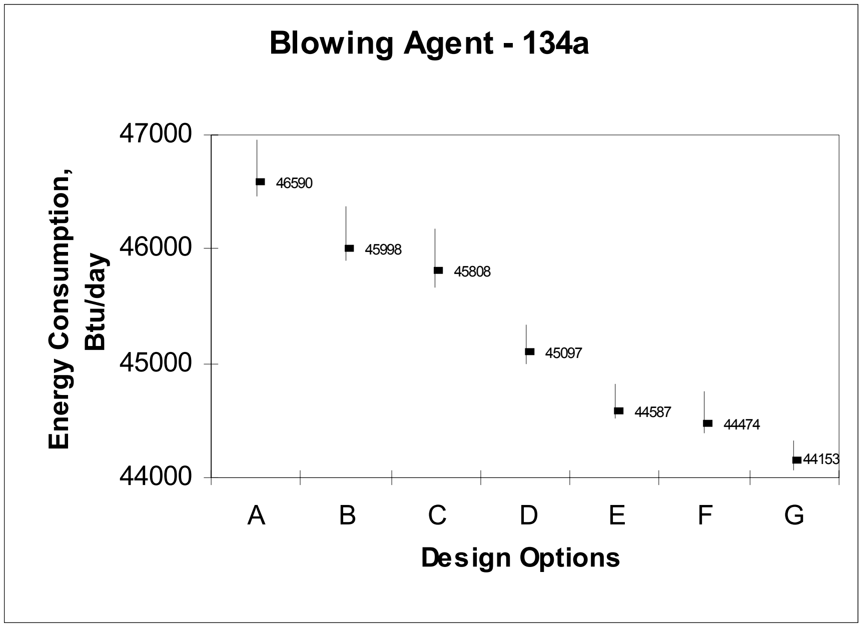

Figure 1 Energy Consumption by Design Option

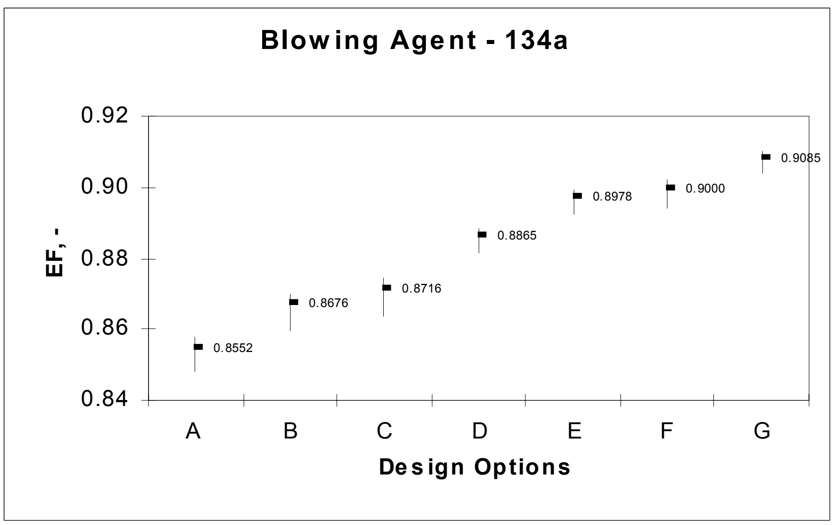

Figure 2 Energy Factor by Design Option

Although for HFC-134a the measured conductivity varies by as much as 15%, the impact on the energy factor value is much smaller. The average for all the design options is 0.0086 of EF or 1% change. With each successive design option, the variation of conductivity has less of an impact on both energy consumption and EF. For example, the impact on the EF varies from 0.0103 (1.2%) on design option B to 0.0067 (0.7%) on design option G. Additionally, as one would expect, as conductivity becomes higher more energy is consumed and the EF decreases.

Efficiency Potentials and Payback Periods

Figures 3 and 4 map payback period by energy factor for each design option with the three blowing agents.

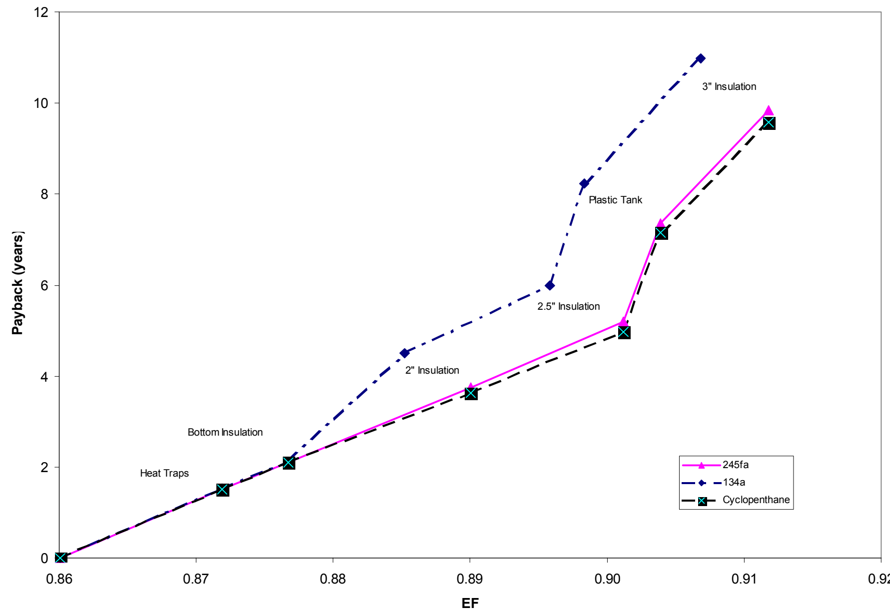

Figure 3. Payback vs. Energy Factor: Electric Water Heaters, 50-gal (190 l)

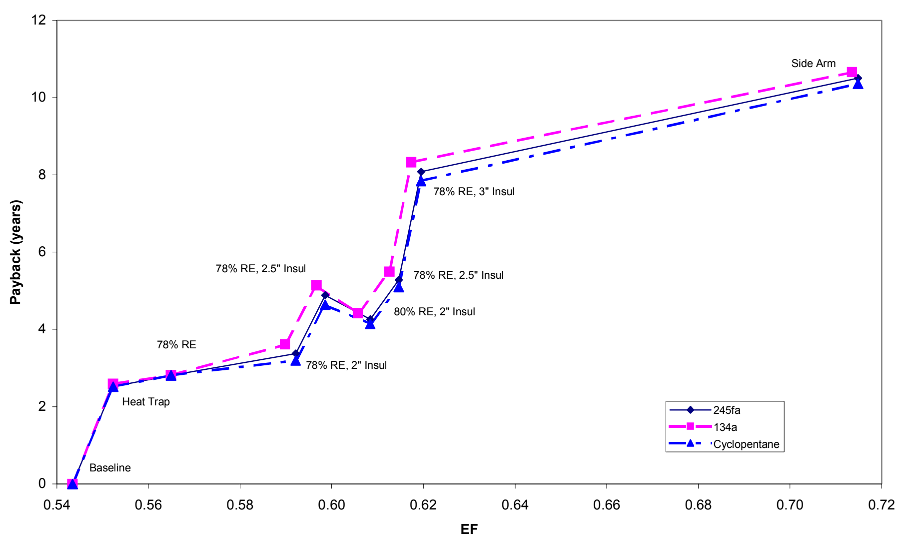

Figure 4. Payback vs. Energy Factor: Gas-Fired Water Heaters, 40-gal (150 l)

For electric water heaters, the baseline unit has the same EF for the three blowing agents because of the need to meet the minimum current efficiency standard. For the first two design options on electric water heaters, the type of blowing agent has little impact on the EF/payback relationship. When the insulation thickness is increased, HFC-134a has the longest payback and the lowest EF due to its lower conductivity and higher cost. While cyclopentane is the least expensive alternative, the capital investment required makes it essentially equal to HFC-245fa. For HFC-245fa and cyclopentane, the highest EF attained was 0.911, achieved using heat traps, 3-in. jacket insulation, an insulated tank bottom, and a plastic tank. The payback period for this design was 9.6 years compared to a baseline unit (EF 0.86). The same design option using the HFC-134a blowing agent, the highest EF attained was 0.907. The payback period for this design was 11 years. Models using HFC-245fa and cyclopentane, incorporating heat traps, 2.5 in. insulation, and an insulated tank bottom had an EF of 0.901 and a payback of 5 years. The same design using HFC-134a has a 0.896 EF and a 6-year payback.

The impact of insulation conductivity is less significant for gas-fired water heaters because most of the heat loss occurs through the flue. The baseline unit has the same EF for the three blowing agents because of the need to meet the minimum current efficiency standard. For the first two design options, the type of blowing agent has little impact on the EF/payback relationship. As the insulation thickness is increased, some variation in the three curves appears but is of little significance. HFC-134a has the longest payback and the lowest EF. Cyclopentane and HFC-245fa have essentially equal values. For the three blowing agents, the highest EF attained was 0.71, achieved using a side arm design, electronic ignition, an improved flue baffle (80% RE), a plastic tank, 3-in. jacket insulation, and heat traps. The payback period for this design was 10.5 years compared to a baseline unit (EF 0.54). Models using HFC-245fa and cyclopentane, incorporating heat traps, 2 in. insulation, and 78% RE had an EF of 0.59 and a payback of less than 4 years.

CONCLUSIONS

This study determined costs of increased energy efficiency for different design options on residential water heaters using three blowing agents.

The results show that in the case of electric water heaters, the HFC-134a blowing agent has approximately 0.1 lower EF and 1-year longer payback for the same design options using the two other alternative blowing agents. The difference is much less significant for gas-fired water heaters because of the larger magnitude of the flue losses, which are not effected by insulation changes. Even though the cyclopentane insulation is the least expensive, the capital investment required (due to its flammability) lengthens its payback.

Although the reported conductivity values for different foam varies as much as 15%, the impact on the energy factor value is much smaller (approximately 1%).This implies that variation attributed to blowing agent aging has a relatively small long-term efficiency impact.

For electric water heaters, it was possible to achieve EFs as high as 0.90 and a payback of about 4 years with HFC-245fa and cyclopentane. For gas-fired water heaters all three insulations considered allowed an energy factor of 0.59 and a payback of about 4.5 years.

By studying the impact of different polyurethane foams in simulated water heater environments, we conclude that at least three blowing agents can be used to achieve similar performance for similar costs to HCFC-141b and to comply with the environmental regulations.

ACKNOWLEDGMENTS

This work was supported by the Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The authors wish to thank Terry Logee (DOE project manager) and Julie Glover (LBNL).

REFERENCES

1. CFR. 1998. Title 10, Code of Federal Regulations, Part 430, Appendix E to Subpart B-Uniform Test Procedure for Measuring the Energy Consumption of Water Heaters.

2. U.S. Environmental Protection Agency-Stratospheric Protection Division, U.S. Environmental Protection Agency, "HCFC Phaseout Schedule", <http://www.epa.gov/ozone/title6/phaseout/hcfc.html>, 1998.

3. Promising Outlook for Polyurethanes. *Appliance Magazine*, 2000. 57(6): p. 68-69.

4. Jefs M., de Vos Rik. Zero ODP Blowing Agents Options for Rigid Polyurethane Insulating Foams. In *Proceedings of the Polyurethanes EXPO' 96*, sponsored by the Polyurethane Division of The Society of the Plastics Industry, Inc. 1996. Las Vegas, NV, October 20-23, 1996.

5. U.S. Department of Energy-Office of Codes and Standards, *Technical Support Document: Energy Efficiency Standards for Consumer Products: Residential Water Heaters*. Washington, DC. December 2000. <http://www.eren.doe.gov/buildings/codes_standards/reports/waterheater/index.html>

6. Elf Atochem. 1999. *Property and Cost Comparison HFCs*, Report.

7. U.S. Department of Energy, *Water Heater Energy Efficiency Standards Workshop, Transcript,* July 23*,* 1999. Washington, DC.

8. McGee, I. E., M. A. Dobransky, and K. A. Ingold, HFC-245fa as a Blowing Agent for Water Heater Foam Insulation. In *Proceedings of the Polyurethanes EXPO' 96,* sponsored by the Polyurethane Division of The Society of the Plastics Industry, Inc. 1996. Las Vegas, NV, October 20-23, 1996: p. 170-173.

9. Wilkes, K. E., W. A. Gabbard, and F. J. Weaver, Aging of Polyurethane Foam Insulation in Simulated Refrigerator Panels -- One-Year Results with Third-Generation Blowing Agents. In *The Earth Technologies Forum,* September 27-29. 1999. Washington, DC.

10. Hiller, C. C., A. I. Lowenstein, and R. L. Merriam, 1992. *WATSIM User's Manual, Version 1.0: EPRI Detailed Water Heating Simulation Model User's Manual.* EPRI. Palo Alto, Calif. Report No. TR-101702.

11. Paul, D. D., G. R. Whitacre, J. J. Crisafulli, R. D. Fischer, A. L. Rutz, J. G. Murray, and S. G. Holderbaum. 1993. *An Interactive Personal Computer Program to Aid in the Design and Analysis of Storage-Type Water Heaters*, Battelle. Columbus, Ohio. Prepared for the Gas Research Institute. Report No. GRI-93/0186.

12. Gas Appliance Manufacturers Association. 1998. GAMA Cost Data. Personal communication, Arlington, VA

13. Minniear, M., *Residential Water Heaters: Initial Estimates of Manufacturing Costs and Energy Consumption*, November 12, 1997, Minniear Corporation. Panama City, FL. LBNL Subcontract No. 6466797.

14. U.S. Department of Energy-Office of Codes and Standards. 1999. *Water Heater Price Database*.

15. U.S. Department of Energy-Energy Information Administration. 1999. *Annual Energy Outlook 1999*. Washington, D.C. Report No. DOE/EIA-0383(99).